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EYE MOVEMENTS, SPATIAL PATTERN VISION, STABILIZED RETINAL IMAGES, APPARENT CONTRAST

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Spatial patterns became substantially less visible when held stationary (stabilized) on the retina. Calculations showed that residual visibility of stabilized high contrast patterns can be attributed to slight failure of stabilization. Stabilization showed further that eye movements play an important role in detection of drifting and flickering grating patterns.

The substantial differences in sensitivity to low-contrast grating patterns of various spatial and temporal frequencies were

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EYE MOVEMENTS AND SPATIAL PATTERN VISION

Eye Research Institute
20 Staniford Street
Boston, MA   02114

Dr. Lawrence F. Arend

not observed when apparent contrasts of high-contrast gratings
were determined.   Approximately equal physical contrasts produced
equal apparent contrasts.

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REPORT: 2/1/83 TO 1/31/84

I. OBJECTIVES

The overall objective of the project is further development of a model (Arend, 1973) describing the role of retinal image motion in the human visual system's processing of edge information in patterns. Several lines of investigation were proposed, including:

A.   Eye Movements and Stabilized Retinal Images

Recent experiments using grating patterns held stationary on the retina have raised questions concerning the role of retinal image motion in spatial pattern vision. The fact that high contrast gratings remain visible when stabilized with the SRI Double Purkinje Image Eyetracker (Kelly, 1979) has been interpreted as meaning that the human visual system can process pattern information in the absence of temporal change of the retinal image, contradicting previous views. This issue is a critical part of the most basic understanding of human pattern vision. A major goal of the first year of the project was examination of PI tracker grating stabilization and Kelly's interpretation of his data.

B.   Suprathreshold Contrast Matching and Temporal Modulation

The model proposes that all pattern information is derived from temporal changes of the retinal image. Useful pattern perception requires that the visual system take the source of the temporal change (eye rotation, object movement, fluctuation of external illumination) into account since the different sources produce different patterns and amplitudes of temporal change for the same external objects. The compensation mechanism has consequences for the relationship between threshold and suprathreshold grating perception. A second goal of the first year was completion of a study of suprathreshold contrast matching of temporally modulated sinusoidal gratings which examines those consequences.

C.   Spatial Gradients and Integration over Edge Information

A large component of the project is investigation of how information from sharp and shallow spatial gradients of intensity and color gets put together into a stable spatial representation of lightness and color. The first year goals for this portion of the project were selection, purchase and installation of a display system consisting of minicomputer, image processor and color video monitor.

II.   STATUS OF RESEARCH EFFORT

A. Stabilized Retinal Images

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Substantial progress was made in evaluating Purkinje Image Eyetracker stabilization of gratings. The principal conclusions are:

1) Most of the gross form of Kelly's grating stabilization data replicates in our lab using a similar eyetracker, different subjects and improved methods.

2) Calculations from unstabilized grating contrast sensitivities show that the P.I. tracker (and, in fact, no existent eyetracker) can eliminate all meaningful retinal image motion and therefore

a) Residual visibility of stabilized objects does not necessarily imply that the visual system contains mechanisms capable of responding to temporally unchanging inputs and
b) Only subjective pattern fading and disappearance can be relied upon as a criterion of stabilization adequacy, and then only with qualification.

In light of current evidence, therefore, it is likely that all pattern information is derived from retinal temporal changes, and some model describing the transfer from temporal information to spatial pattern is required.

1) Stabilized Contrast Sensitivities. The first portion of the year was devoted to setting up optics and electronics to stabilize gratings on the retina with a generation IV SRI Purkinje Image Eyetracker. A high luminance monitor (Tektronix 608) was purchased and electronics were designed and constructed to display vertical cosine luminance gratings. The horizontal analog eye position voltage from the tracker was sampled and digitized 140 times per second, at the beginning of each display frame, and the phase of the grating was offset to produce constant phase on the retina.

For the initial work conditions similar to Kelly's were used since we were attempting to replicate his results. A few procedures were slightly improved to increase control. The temporal rate of change of contrast in the adjustment procedure was constant, under computer control. In Kelly's experiments the subject initially viewed the pattern at an unspecified high contrast for an unspecified duration in order to rapidly build up the afterimage. This procedure gave highly variable results in our early work so we held the initial contrast constant at 0.6 for 20 seconds.

In fig. 1 are mean log sensitivities for stabilized gratings with superimposed drift velocities of 0, 0.012, 0.15, and 3 degarc/s. The general magnitude of the effect of pattern velocity and the overall shapes of our curves agree with Kelly's (Kelly,1979). Under these stabilization conditions the motionless grating threshold was elevated by a factor of 50 over the 0.15 deg/s threshold at 1 c/deg, decreasing monotonically to a factor of seven at 8 c/deg. Imposing a drift velocity of only 0.12 deg/sec (roughly twice the foveal intercone distance per

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Fig. 1

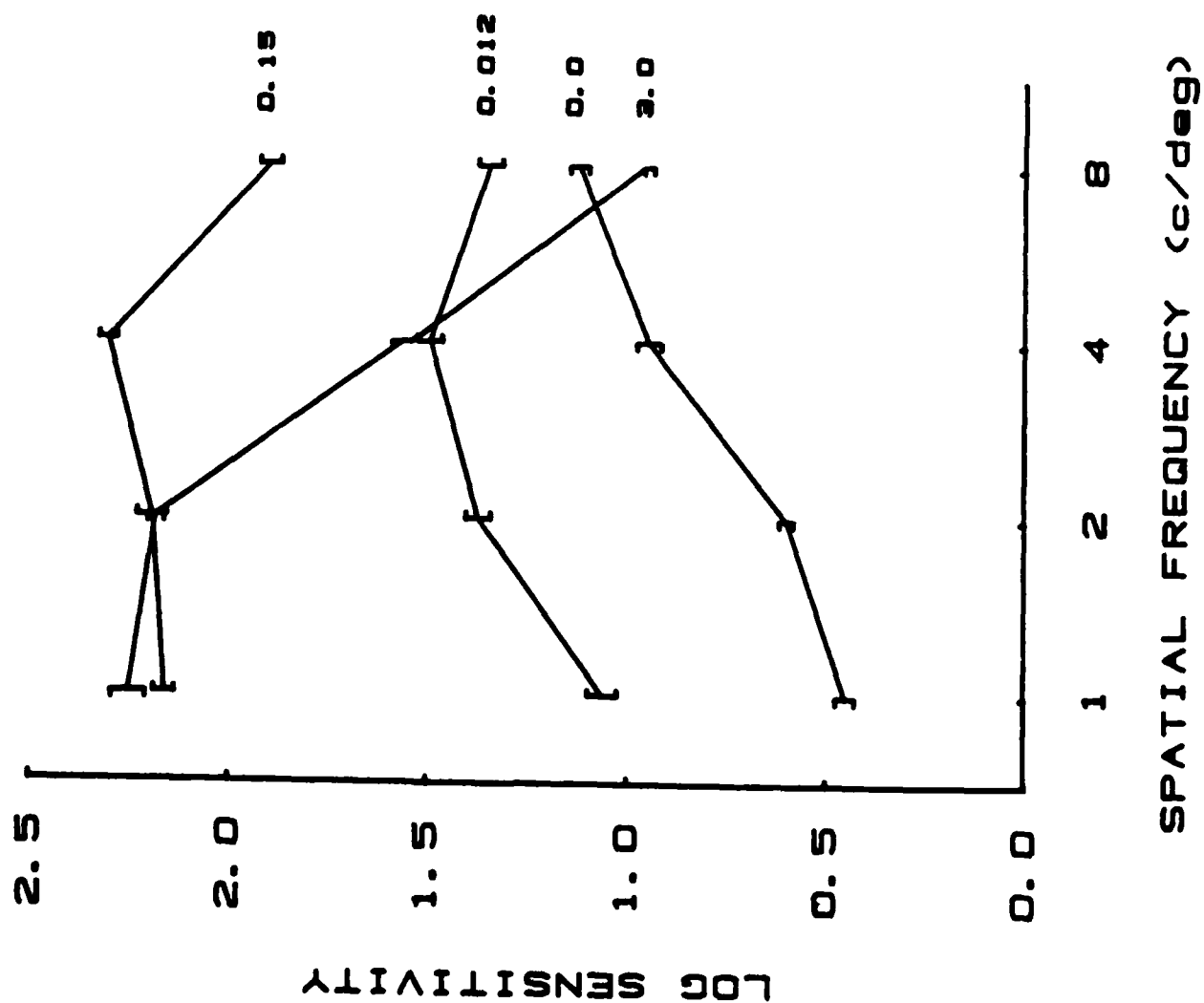LOG SENSITIVITY

SPATIAL FREQUENCY (c/deg)

Figure 1. Mean log sensitivities for stabilized gratings with superimposed constant-velocity drifts. Parameter: drift velocity in degarc/s. S: LA.

second of time) increased sensitivity by as much as 0.75 log units.

The fact that the zero-velocity log sensitivies do not drop to zero has been interpreted by Kelly and others to mean that the visual system is capable of detecting temporally unchanging gratings of sufficiently high contrast. This interpretation is very attractive since it greatly simplifies the early visual encoding of pattern. It would provide pattern vision modellers some (though still inadequate) justification for ignoring eye and head movements. It holds, however, only if one can believe that all important temporal change has been eliminated by the stabilization. Some of Kelly's data suggest that extremely small temporal changes might be psychophysically important, so one goal of the first year was development of a means of quantitatively evaluating the importance of small residual retinal motion of the "stabilized" gratings.

I found that the importance of small oscillations can be evaluated by a relatively simple calculation. A grating sinusoidally oscillating on the retina over a distance which is small relative to one grating period is approximately the sum of two perfectly stabilized gratings. One is temporally-constant and high-contrast; the other is temporally counterphase modulated and of low contrast:

$$L(x,t) \approx L_M [1 + C_S \sin 2 \pi f x +$$

$$(C_S 2 \pi f \gamma)(\cos 2 \pi \nu t)(\cos 2 \pi f x) \qquad (1)$$

where $L(x,t)$ is the distribution in space and time, L_M is the mean luminance, C_S is the grating contrast, and γ and ν are the amplitude and temporal frequency of the grating's oscillatory movements.

The second term of equation (1) is a counterphase modulated grating of contrast $C_S 2 \pi f \gamma$. If we assume:

1) as noted above, that γ is small relative to one grating period and
2) the presence of the high-contrast stationary component is neither directly detectable nor indirectly affects detection by altering the sensitivity to the temporally modulated component

then equation 1 provides a link between measurable sensitivity to counterphase-modulated gratings and sensitivity to sinusoidally oscillating gratings, i.e.,

$$C_{\nu,f} = C_S 2 \pi f \gamma \qquad (2)$$

where $C_{\nu,f}$ is the measured threshold contrast for a counterphase-modulated, stabilized grating of temporal and spatial frequencies of ν and f, respectively[1] and the other quantitites are as in equation 1. From this relation we can

[1]The measurement requires that the counterphase modulation be greater than temporal modulation due to inadequate stabilization.

calculate, for example, the amplitude, γ , of 4-Hz motion of a 2 c/deg, 100% contrast grating which would produce just-detectable temporal change on the retina. In stabilized counterphase grating experiments $C_{4,2}$ is observed to be about 0.014. Therefore,

$$\gamma = C_{y,f}/C_s 2 \pi f = 0.014/4 = 0.0011 \text{ deg amplitude,}$$

or 8 secarc pk-pk. Since no existing eyetracker can avoid such small movements a 100% contrast, 2 c/deg grating cannot be made to disappear by stabilization alone; the visual system is remarkably sensitive to retinal movement of such spatiotemporal patterns.

While the conclusions are robust when the conditions are met (i.e., the math is straightforward) we decided to collect data allowing direct comparison of thresholds for wiggling and counterphasing gratings.

In fig. 2 are plotted temporal CSFs for two conditions. The points with right-hand error bars are mean log sensitivities for 1 c/deg stabilized gratings, counterphase modulated at the abscissa frequencies. The sensitivities in the other curve were calculated (using eq. 2) from thresholds for stabilized 1 c/deg gratings moved sinusoidally at the abscissa frequencies over a pk-pk distance of 3.33 minarc. The agreement is excellent through 4.4 Hz. The second assumption underlying eq. 2 is obviously suspect with respect to the breakdown at higher temporal frequencies, but a detailed explanation is not yet clear.

In fig. 3 are comparisons of thresholds for gratings drifting or counterphase flickering at 4.4 Hz. For unstabilized gratings the ratio of the thresholds decreases with increasing spatial frequency (e.g., Watson, et al, 1980). We found, as Kelly did, that the ratio of thresholds for the two modulation conditions was independent of spatial frequency for stabilized gratings. However, our ratio was closer to that found by Watson, et al for unstabilized low spatial frequency gratings than to Kelly's ratio of two. In unstabilized viewing the observed ratio decreased as spatial frequency was increased. Comparison of the stabilized and unstabilized curves showed that retinal image motion due to eye movements enhances detection of high spatial frequency gratings for both temporal modulation types, but more for counterphase flicker than for drift.

We have recently collected some data in an initial effort to tease apart several adaptation processes contributing to the threshold elevations in fig. 1. In fig. 4 are spatial CSF's for 0.15 °/s drifting gratings (included because it is similar to the unstabilized, free-viewing spatial CSF) and for a condition with adaptation and criterion identical to the 0 °/s curve of fig. 1, but with voluntary fixation (subject attempting to suppress saccadic eye movements) rather than tracker stabilization. Comparison of these curves shows that the adaptation procedures and voluntary limitation of eye movements account for a substantial portion of the threshold elevation of fig. 1. Nevertheless, the 4 c/deg point of the 0 °/s curve, fig. 1, is 0.9 log units below the corresponding voluntary fixation point of

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Figure 2. Mean log sensitivities for 1 c/deg gratings temporally modulated by two methods. Right-facing error bars: stabilized, counterphase-flicker. Left-facing error bars: stabilized, moving sinusoidally, pk-pk movement = 3.33 minarc, sensitivity calculated from equation 2. S: LA.

Figure 3. Mean log sensitivities for drifting and flickering gratings. Circles: 4.4 Hz drift. Squares: 4.4 Hz counterphase flicker. Solid line: stabilized. Dashed line: unstabilized. S: LA.

Figure 4. Mean log sensitivities. Bottom curve: zero-velocity stabilized curve from fig. 1. Middle curve: unstabilized, voluntary-fixation, with adaptation and criterion identical to bottom curve. Top curve: 0.15 deg/s curve from fig. 1.

Figure 5. Mean log sensitivities. Bottom curve: zero-velocity stabilized curve from fig. 1. Middle curve: stabilized curve from ascending method of limits. Top curve: unstabilized curve from ascending method of limits.
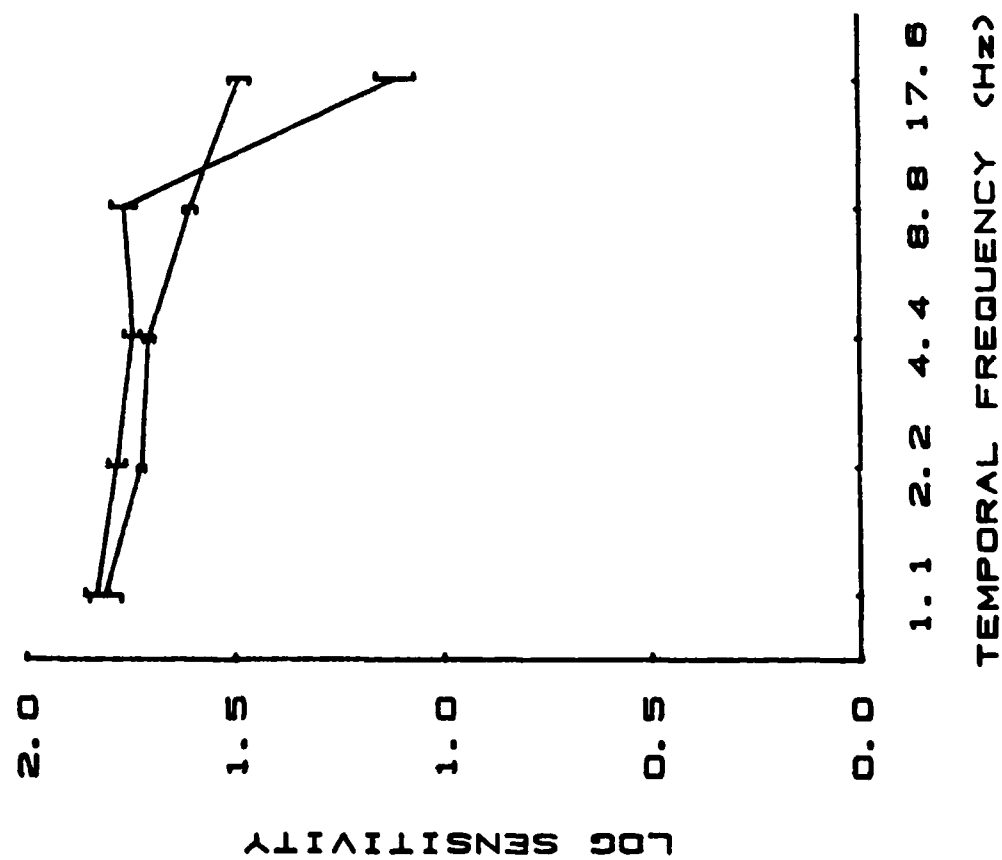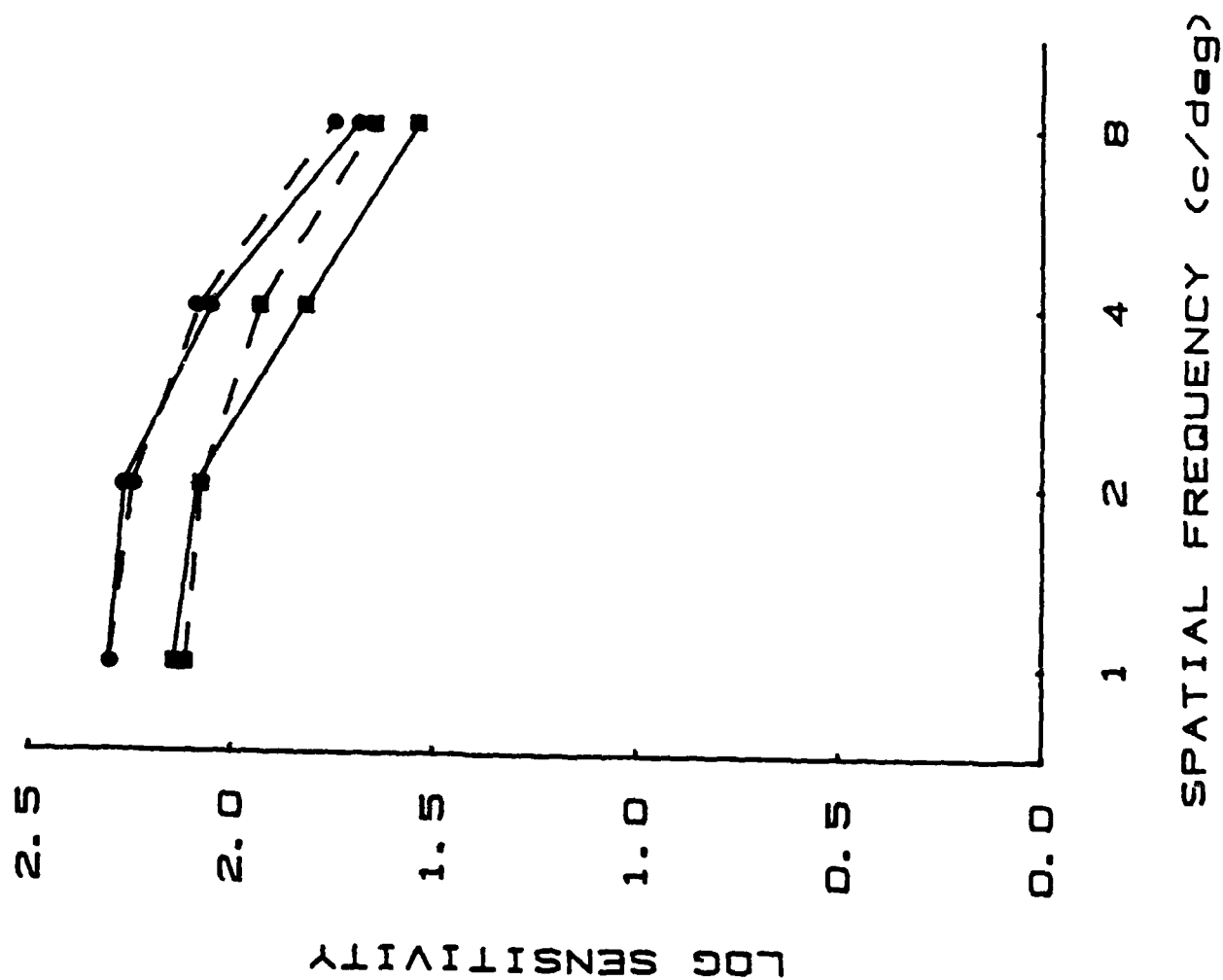
Fig. 2

LOG SENSITIVITY

TEMPORAL FREQUENCY (Hz)

1.1 2.2 4.4 8.8 17.6

2.0   1.5   1.0   0.5   0.0

Fig. 3

LOG SENSITIVITY

2.5
2.0
1.5
1.0
0.5
0.0

1   2   4   8

SPATIAL FREQUENCY (c/deg)

Fig. 4

SPATIAL FREQUENCY (c/deg)
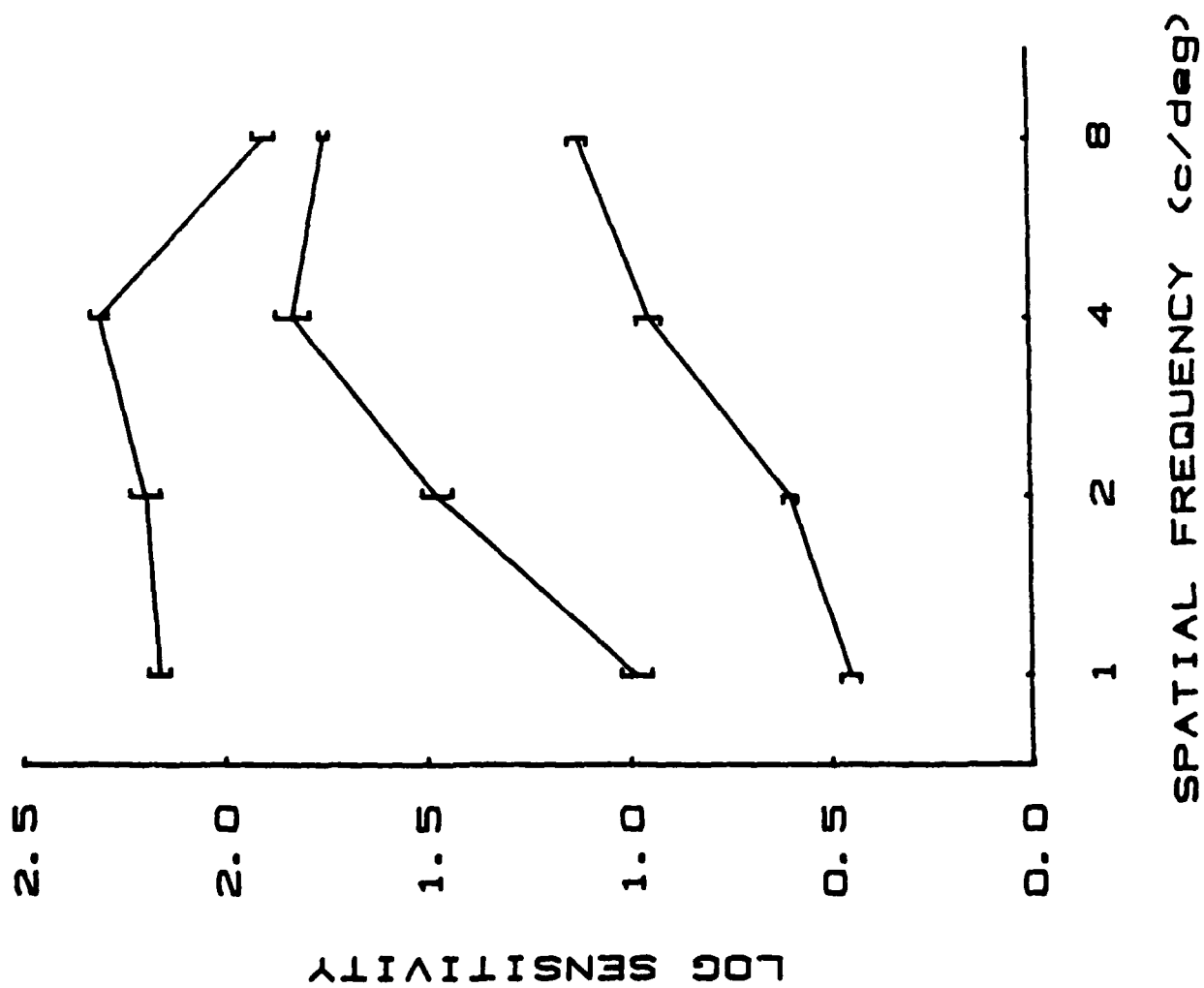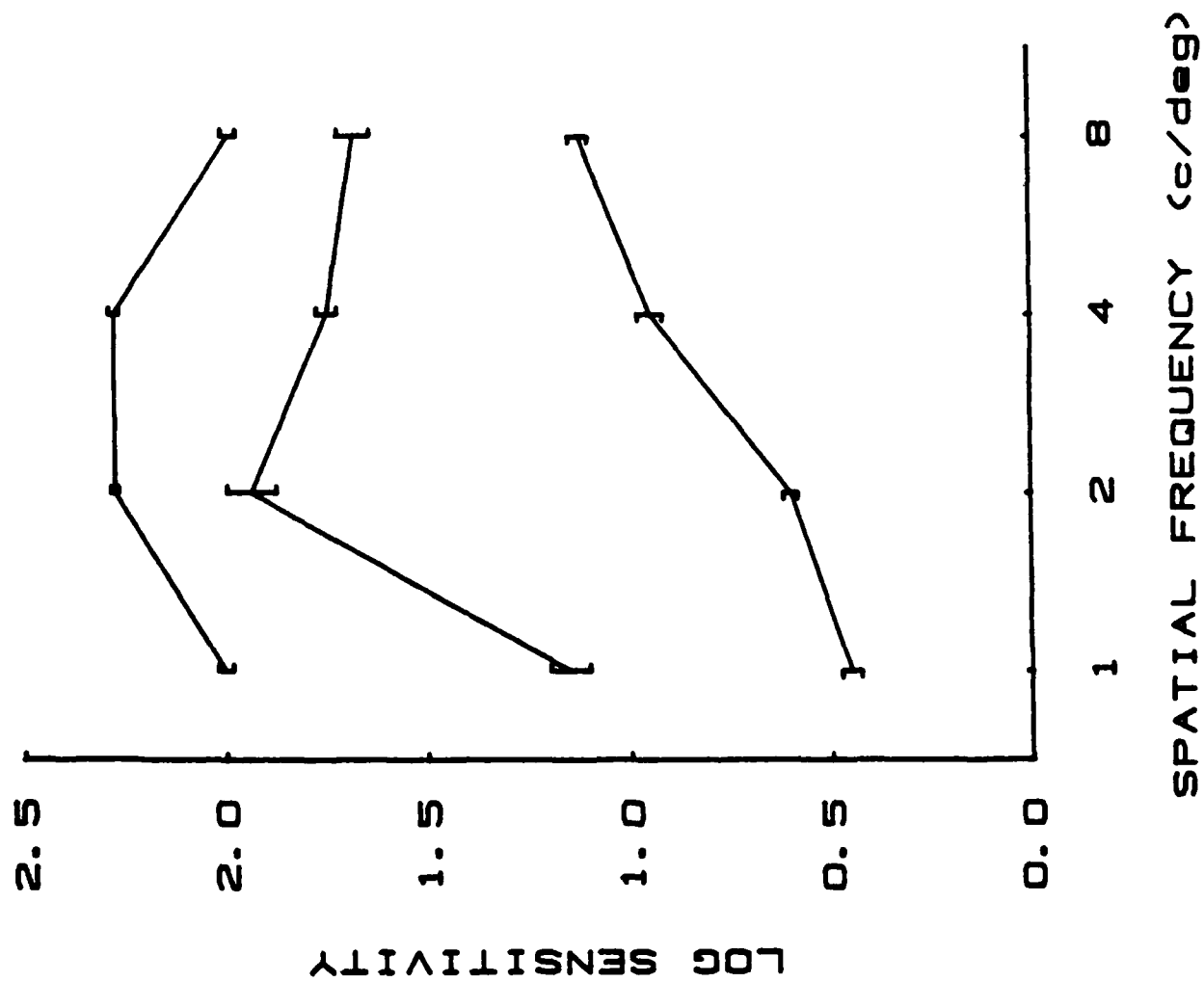
LOG SENSITIVITY

Fig. 5

fig. 4, showing a very substantial contribution of eyetracker stabilization.

In fig. 5 are curves collected using adaptation and criterion procedures similar to those designed by Burbeck and Kelly (1984). Their procedures were intended to minimize duration of exposure to suprathreshold gratings and therefore hopefully reduce some of the contributing adaptive processes more than others. The bottom curve is the zero-velocity curve from fig. 1, included for comparison purposes. The upper curve is for unstabilized viewing with the subject moving the eyes to subjectively maximize sensitivity. The middle curve is for tracker stabilization. For both of the upper curves the plotted points are the mean log end points of five ascending method of limits runs. For each run the grating contrast was set well below the threshold, and after 20 s a tone indicated the beginning of a 5 s test period. The contrast was increased by 0.05 log units at the end of the test period and the cycle repeated until the subject reported the grating visible throughtout the 5 s test period.

Under these conditions Burbeck and Kelly (1984) found much less threshold elevation than in Kelly's original experiments, with no significant threshold elevation due to stabilization at frequencies above 2 c/deg. We found that stabilization under these conditions still produced substantial threshold elevation, even at 8 c/deg. While these data must be replicated with a second subject, it appears that less of the elevations in fig. 1 may be attributed to nonlocal grating adaptation thanindicated by Burbeck and Kelly's data. This is the first substantial disagreement of data from the same experiment in the two laboratories (but not, obviously, of interpretation).

B. Suprathreshold Contrast Matching and Temporal Modulation

The shape of the spatial contrast sensitivity function depends strongly on the temporal modulation of the gratings. The model attributes much of that dependence to differences between the patterns of temporal change produced by retinal image motion versus temporal modulation of the viewed pattern. Approximately veridical contrast perception requires that the source of temporal change be taken into account at high pattern contrasts to offset different efficiencies of the various ways a particular pattern may be temporally modulated. In other words, the substantial differences between contrast thresholds for various spatial and temporal frequencies should be reduced or eliminated at high physical grating contrasts.

In pilot work I found preliminary evidence that temporal modulation had a much smaller effect on the shape of suprathreshold contrast matching functions than at threshold. This work has been completed in the first year. In fig. 6 are low spatial frequency threshold and contrast matching surfaces and in fig. 7 are the corresponding surfaces for high spatial frequencies. For the threshold surfaces the subject adjusted gratings on half the display screen to detection threshold. For the contrast matching surfaces the subject adjusted the contrast of the test grating on half the screen to match the apparent

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contrast of a standard, 2 c/deg grating of fixed contrast presented on the other half screen.

Even at these moderate contrasts (30%) there was very little difference in the physical contrasts required to match the standard. As the model predicted, equal physical contrasts produced approximately equal apparent contrasts over a broad range of spatial and temporal frequencies, in spite of large differences in the retinal temporal changes produced by the various patterns.[2]

As noted above (fig. 3) the threshold amplitude for drifting stabilized gratings is substantially less than the threshold for counterphase flickered gratings. For unstabilized gratings the ratio of the unstabilized thresholds depends on the spatial frequency (Watson, et. al., 1980). The relationship between the thresholds has been analyzed in terms of the responses of medium spatial bandwidth detector mechanisms, and in my previous work I have shown that apparent contrast of suprathreshold gratings is also determined by medium bandwidth mechanisms. In the first year we also examined the ratio of matching contrasts for drifting and flickering gratings. In fig. 8 are the differences between the mean log thresholds for drifting and flickering gratings and the differences between the mean log matching contrasts for several spatial frequencies. As in earlier experiments the threshold is much higher for counterphase flickered gratings than for drifting at low spatial frequencies. The counterphase-flicker physical contrasts matching the apparent contrast of a drifting grating also had to be higher at most frequencies, but only slightly. The fact that stabilization eliminated the effect of spatial frequency on the threshold ratio (fig. 3) suggests that the convergence of the threshold and contrast matching curves at high spatial frequencies may be due to eye movements, but no stabilization data have been collected at this point.

C. Display System

During the first year a display system consisting of a VAX 11/750 minicomputer, an Adage 3000 image processor and a Tektronix 690 RGB monitor was selected, purchased, and installed. In the course of further investigation of the equipment originally specified it became clear that several changes were necessary. The research plan required higher temporal and color resolution than originally specified. The Adage 3000 actually purchased has 10-bit digital/video converters and runs at 60-Hz, repeat-frame.

In discussions of my original computer specifications with members of Digital Equipment Corporation's display design team they became interested in potential implications of the research for design of color graphics display equipment. In return for my giving two talks to their design teams describing the results of experiments from my original proposal Digital provided a grant

[2]In the interim Bowker (1983) has published spatiotemporal contrast matching surfaces and noted the relative contrast constancy. He used a less satisfactory matching method so his data are somewhat less convincing due to high variability.

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Figure 6.   Spatiotemporal threshold and suprathreshold contrast surfaces--Low spatial frequencies. Lower surface: mean log threshold contrasts for base-plane spatial and temporal frequencies.   Upper surface: mean log physical contrast of gratings matching apparent contrast of 2 c/deg standard gratings.

Figure 7.   Spatiotemporal threshold and suprathreshold contrast surfaces--High spatial frequencies. Lower surface: mean log threshold contrasts for base-plane spatial and temporal frequencies.   Upper surface: mean log physical contrast of gratings matching apparent contrast of 2 c/deg standard gratings.

Figure 8.   Differences between mean log matching contrasts for drifting and flickering gratings. Open circles: subject LA, threshold. Closed circles: threshold points from Watson, et al, (1980).   Open squares: subject LA, apparent contrast match, 0.7 C, 2 Hz. Closed triangles: subject RA, apparent contrast match, 0.7 C, 3 Hz.
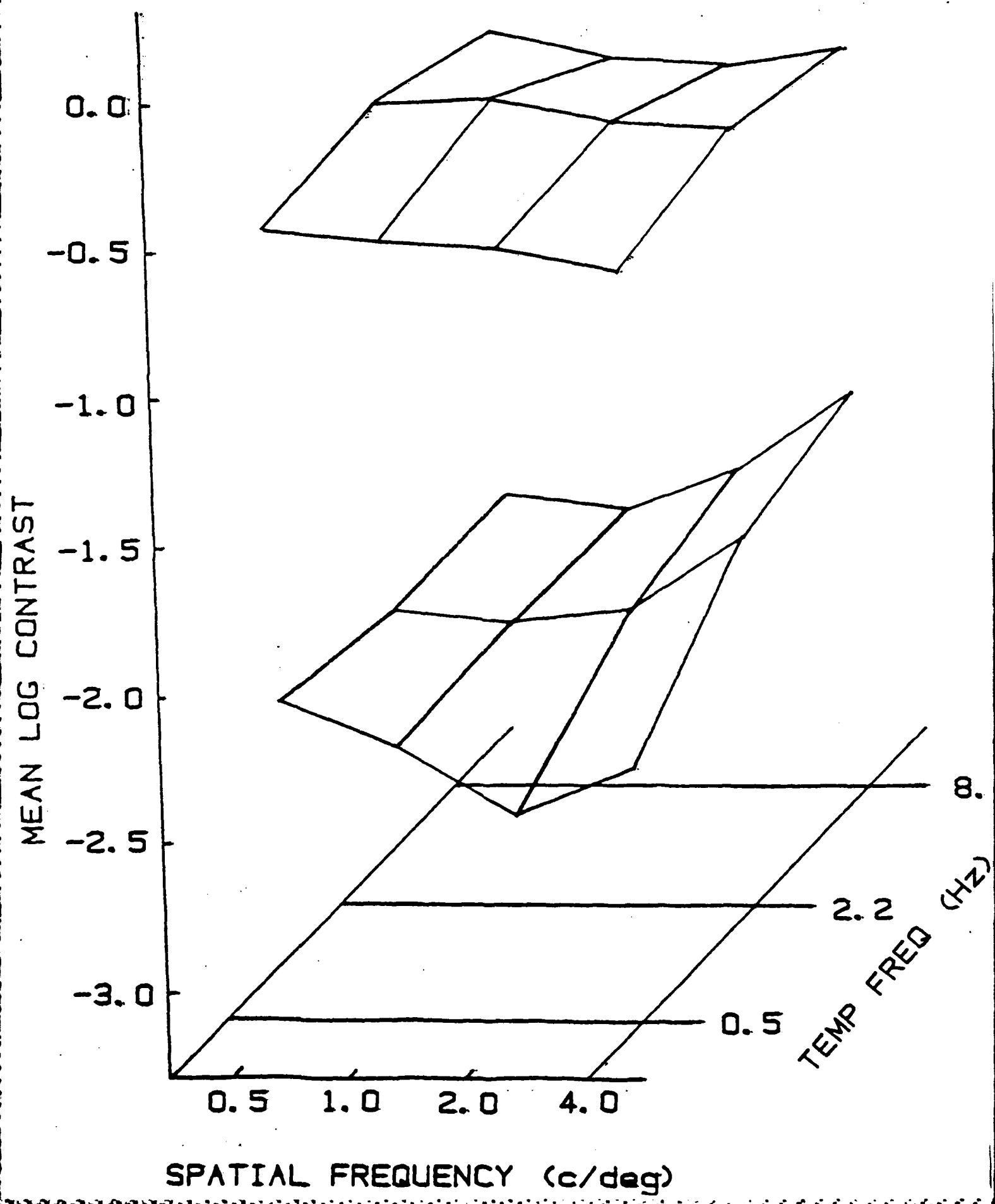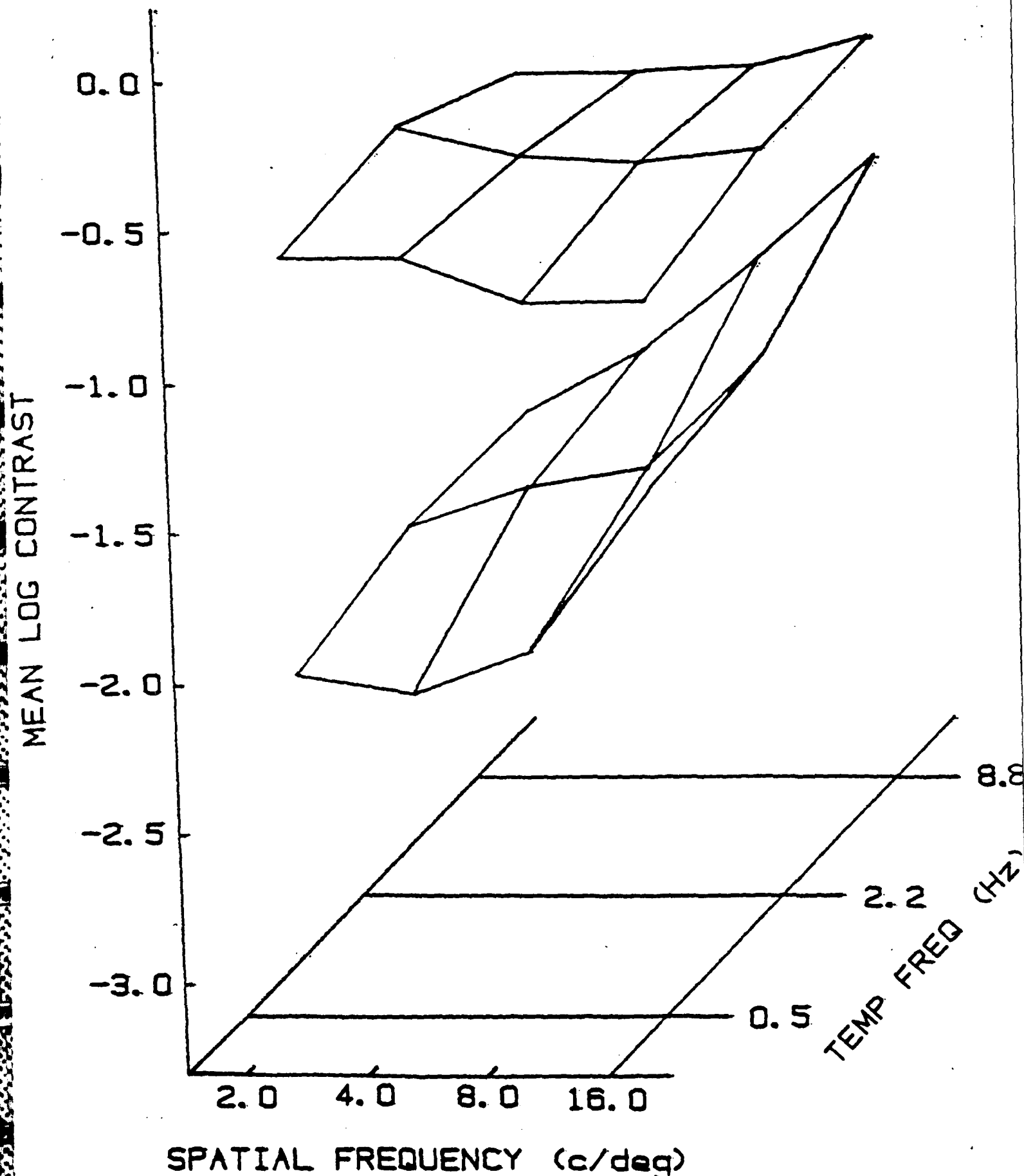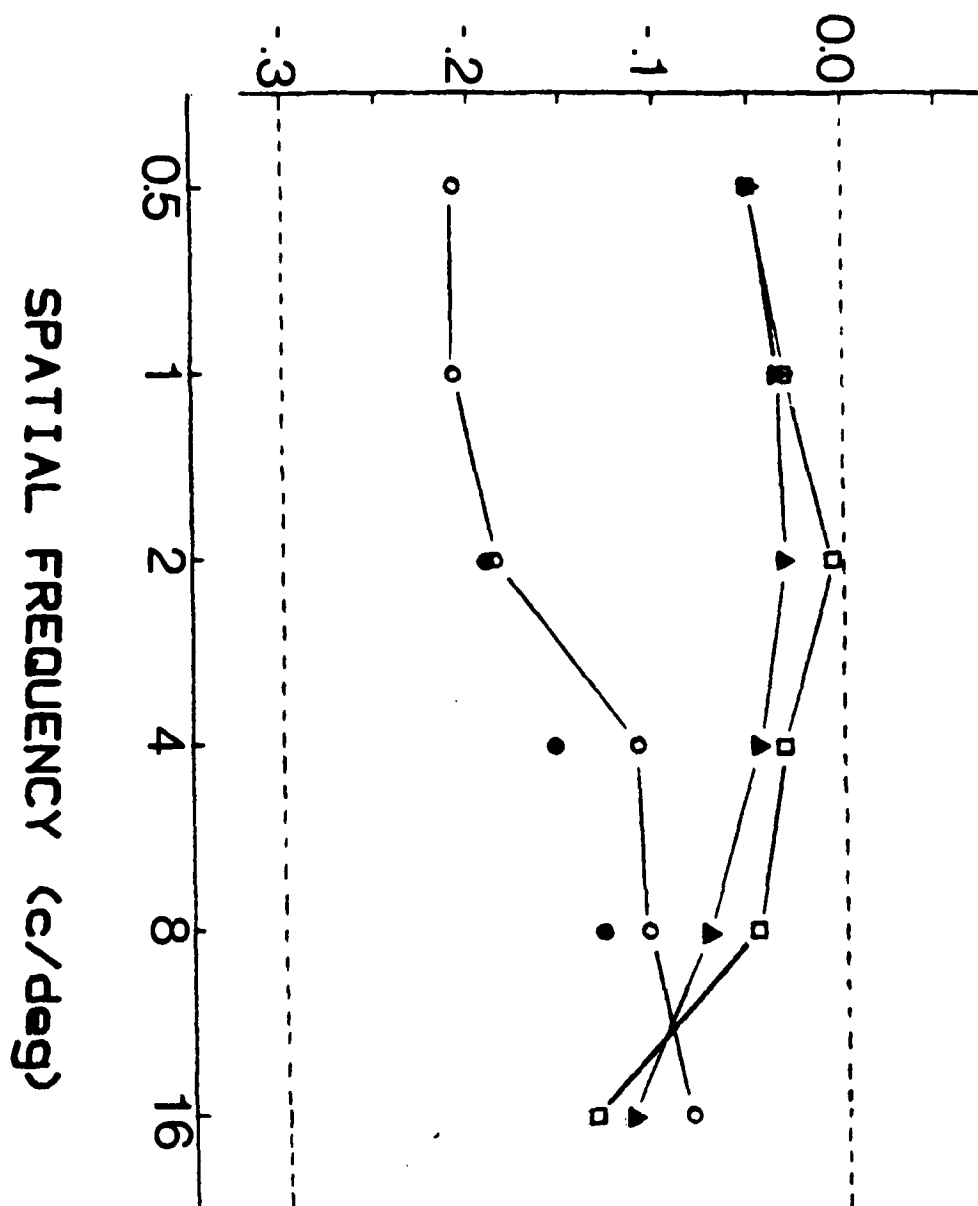
Fig. 6

FIG 7

MEAN LOG CONTRAST

0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0

8.8
2.2
0.5

TEMP FREQ (Hz)

2.0   4.0   8.0   16.0

SPATIAL FREQUENCY (c/deg)

LOG DRIFT – LOG FLICKER

SPATIAL FREQUENCY (c/deg)

of one-half the purchase price of the VAX 11/750 system.

While significant delivery delays have been encountered on some of the equipment ordered (computer memory, disk packs, terminal) all major equipment is now installed and running. Modifications of low-level software for controlling the Adage are well along, and calibration of the RGB monitor should begin in approximately one week.

Experiments using the system should begin in about two months, following completion of programs to control color output, select and display stimuli, log data, etc. Many of the routines are available on the microcomputer system and need only be translated from BASIC to FORTRAN and adapted to the new machine.

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III. PAPERS IN PREPARATION

Arend, L. E. and Lange, R. V. Apparent contrast of suprathreshold spatiotemporal gratings. (Probably to be submitted to <u>Vision Research</u>).

Arend, L. E. and Timberlake, G. T. How good must retinal image stabilization be? (Probably to be submitted to <u>J. Opt. Soc. Amer.</u>).

IV. PROFESSIONAL PERSONNEL

Arend, Lawrence E., Principal Investigator

Lange, Robert V., nonsalaried part-time collaborator

Timberlake, George T., nonsalaried part-time collaborator

V. PROFESSIONAL TALKS PRESENTED

Smith-Kettlewell Institute for Visual Sciences, colloquium on eyetracker stabilization, November, 1983.

Stanford Research International, informal presentation of eyetracker data to C. Burbeck and D. Kelly, November, 1983.

END

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